Modelling supply chain network for procurement of food grains in India

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Abstract

The procurement of food grains from farmers and their transportation to regional level has become decisive due to increasing food demand and post-harvest losses in developing countries. To overcome these challenges, this paper attempts to develop a robust data-driven supply chain model for the efficient procurement of food grains in India. Following the data collected from three leading wheat producing Indian regions, a mixed-integer linear programming model is formulated for minimising total supply chain network costs and determining number and location of procurement centres. The NK Hybrid Genetic Algorithm (NKHGA) is employed to cluster the villages, along with a novel density-based approach to optimise the supply chain network. Sensitivity analysis indicates that policymakers should focus on creating an adequate number of procurement centres in each surplus state, well before the start of the harvesting season. The study is expected to benefit food grain supply chain stakeholders such as farmers, procurement agencies, logistics providers and government bodies in making an informed decision.

Keywords: Food supply chain, Modelling and optimization, Food grains, Clustering, Genetic algorithm, Procurement

1. Introduction

According to the UN's Food and Agricultural Organization, approximate 1.3 billion tons, i.e. more than one-third of the food produced globally is wasted annually (Gustavsson et al. 2011). In the majority of developing nations, close to half of all food grains are wasted due to lack of technical efficiency to store them (Kumar and Kalita 2017). Annually, India loses 67 million tons of food, which is higher than the national output of few developed countries (e.g. UK, France). The monetary value of these losses is predicted at USD 13.37 billion (Jha et al. 2015). From the sustainability perspective, the global share of annual carbon dioxide emission from the transportation activities in 2018 was around 24% (Teter et al. 2019). India is one of the largest emitters of global greenhouse gases globally and is ranked third after China and the USA (Timperley 2019). In particular, road transport in India contributes to 261 tons of CO_2 emission daily (Shrivastava et al. 2013). Transportation emission severely affects human health and environment. Lancet Commission on pollution and health ranked India first in pollution-related deaths (2.51 million deaths in 2015) (Landrigan et al. 2017). Due to the heightened air pollution and climatic factors, the crop yield in India has decreased significantly. Every year, pollutant gases damage approximately 5 million tons of crops (wheat and rice) in India (Ramanathan et al. 2014). Therefore, it is imperative to consider the sustainability perspective while dealing with Food Supply Chain (FSC) problems (Banasik et al. 2019; Mohammed and Wang 2017). Generally, sustainability is represented by the *'Triple Bottom Line'* and suggests an integration of economic, environmental and social goals (Carter and Rogers 2008).

The Food Corporation of India (FCI), the nodal organization in collaboration with other state agencies and policymakers in India, conducts the majority of FSC operations. The FSC network is particularly complex in developing country like India, as there is hardly any scientific approach followed while making procurement and distribution-related decisions. By carefully studying existing food grain production, procurement and distribution activities, an integrated food grain supply chain network in India is developed in Figure 1. Food grain supply chain network has four key nodes namely- procurement, intra-state transportation (among different regions within the state), inter-state distribution (across different states- mostly from surplus states to deficit states) and, finally, transportation of food grains from district level warehouses (DLW) to the end delivery points known as Fair Price Shops (FPS). The last stage of transportation from storage point (at regional level) to end customer (a population that falls below the poverty line) via FPS, known as the Public Distribution System (PDS).

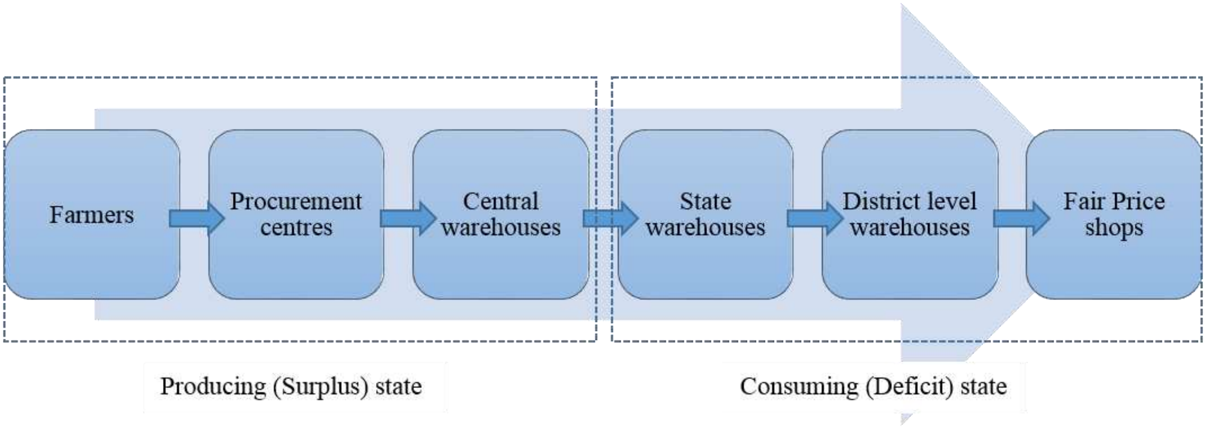

Figure 1 Operations involved in food grain supply chain in India

Due to an escalating population and post-harvest losses, there is a need for increased production, procurement and reduction of losses to feed the growing population of India. Production has increased recently due to the use of advanced agricultural technologies (Sharon et al. 2014). However, policymakers still face challenges associated with an increase in procurement and reduction of food losses (Sharon et al. 2014; Kumar and Kalita 2017; Mogale et al. 2017a; Parwez 2014). India is the second-largest food gain producer after China (Khatkar et al. 2016). The annual food grain production in 2017-18 was 284.83 million tonnes, which was 9.72 million tonnes higher than the previous year (Mohan 2018). Most of the food-producing states in India have a shortage of sufficient and adequate number of procurement centres, which means farmers lose their chance of bargaining for their produce. Multiple farmers face difficulty while aggregating their produce and moving to distant procurement centres to gain the benefit of minimum support price (MSP) through an auction system. This leads these farmers to sell their produce to local agents and traders at locally determined prices, which are far less than the MSP. This intermediation deprives farmers of realising the optimal MSP. One of the main objectives of FCI is to provide price support operations to farmers to safeguard their interest in food grain production. However, FCI is facing issues to offer this support to farmers. Due to unavailability of procurement centres, state government agencies in producing state keeps the food grain stock in the open space, which deteriorates food grain quality and increases losses. To overcome food losses and food shortages in the procurement of food grains in India, the study aims to develop an integrated analytical model to make informed decisions for optimal procurement centres during different harvesting seasons.

Data available from three wheat producers in India was analysed using a machine-learning algorithm. The NK Hybrid Genetic Algorithm (NKHGA) was employed to cluster the villages, along with a novel density-based approach to select the candidate locations for the establishment of procurement centres. A mixed-integer linear programming model was formulated considering maximum distance criteria, transportation difficulty coefficient, heterogeneous capacitated vehicles and limited availability.

The rest of the paper is structured as follows. Relevant literature on food supply chain challenges and modelling approaches are presented in Section 2. The problem description is discussed in Section 3. Section 4 explains the proposed mathematical formulation for the Indian food grain supply chain network. The solution approach is discussed in Section 5. Explanation of the three cases is presented in Section 6. Section 7 delineates the case study results and insights evolved through sensitivity analysis. Finally, concluding remarks and suggestions for further research are provided in Section 8.

2. Literature review

2.1. Procurement challenges in food supply chains

The lack of speedy information, excessive complexity and ineffective practices of traditional procurement systems drive supply chain costs and time (Boer et al. 2002; Mukherjee 2001). The mismatch between supply and demand leads to several procurement challenges in FSCs (Sahle et al. 2018). The lack of an effective framework to quickly manage variations in the market is one of the major challenge in FSCs (Fang Du et al. 2009). The absence of appropriate planning and management practices including inefficient procurement, storage and transportation are the major causes behind substantial post-harvest losses (Shukla and Jharkharia 2013; Murthy et al. 2009).

Moreover, farmers and small-scale industries possess low bargaining power in agri-business (Wardana 2006). Farmer's involvement in the traditional and contemporary market is dependent on the availability of market characteristics (Suryaningrat et al. 2015). Gorton et al. (2006) shed light on the distorted information between the farmers and processors, leading to market failure in Moldova. The impact of food contamination and subsequent recalls on supply chain activities are another set of challenges faced by FSC (Piramuthu et al. 2013; Chebolu-Subramanian and Gaukler 2015). In the USA, processed food and fresh produce travel on an average 1300 and 1500 miles, respectively (Hill 2008). This higher food miles leads to higher fuel consumption, carbon emission, pollution, environmental degradation and global warming (Rajkumar 2010). High level of collaboration between producers and cooperatives may help to reduce such losses (Ghadge et al. 2017; Despoudi et al. 2018). The simultaneous consideration of food quality and sustainability has made the food supply chain more complex (Van Der Vorst et al. 2009).

The food losses also increase due to the inefficient utilisation of resources and ineffective policies (Parfitt et al. 2010). Several major issues associated with FSC such as unscientific and skewed procurement process, inadequate storage facilities, improper planning and coordination decisions, leakages and irregular distribution of food grains are highlighted by multiple scholars in their studies (e.g. Mahapatra and Mahanty 2018; Maiyar et al. 2015; Balaji and Arshinder 2016; Parwez 2014; Viswanadham 2006). According to the Dalwai Committee Report on doubling farmers' income (2017), approximately 70% of the rice and wheat produced in 14 years was not procured by FCI /State Government agencies (from 2002-03 to 2017-18). Swaminathan report of National Commission on Farmers (2004) stated that at least one procurement centre should be available within a radius of five km of a village, but most of the farmers travel on an average thirty km to reach to the nearest procurement centres. This leads to the escalation of transportation cost, travel time and carbon emissions. In India, farmers annually lose USD 9.139 billion, as they are unable to sell their produce (Mahapatra 2018).

2.2 Modelling approaches for FSCs

The management of food supply chains is receiving growing attention from researchers and practitioners (Akkerman et al. 2010; Amorim et al. 2016; Tsolakis et al. 2014). Esteso et al. (2018) and Zhu et al. (2018) conducted a critical review on FSC problems and highlighted varying issues ranging from farmer's welfare, integration of supply chain functions, sustainability and need for decision support models. Interested readers can refer to Ahumada and Villalobos (2009), Beske et al. (2014), Soysal et al. (2012) and Brandenburg et al. (2014) for more details on FSCs problems.

Majority of the research work related to procurement models are scenario specific and are lacking in generic models. Table 1 presents multiple modelling approaches being followed to solve FSC problems. Single objective models in the form of mixed-integer programming by taking into account the facility establishment and variable transportation cost have been widely explored in the past literature (e.g. Khamjan et al. 2013a; Neungmatcha et al. 2013; Nourbakhsh et al. 2016; Mohammadkhanloo and Bashiri 2013). However, the fixed transportation cost of heterogeneous capacitated vehicles and emissions costs have received limited attention.

Table 1 Comparison of recent literature in the food supply chain context

Model: *LP: Linear Programming, LIP: Linear Integer Programming, MIP: Mixed Integer Programming, MILP: Mixed Integer Linear Programming, MINLP: Mixed Integer Non-Linear Programming,*

Objective function components: *FLC: Facility Location Cost, FTC: Fixed Transportation Cost, VTC: Variable Transportation Cost, OC: Operational Cost, EC: Emission Cost; HCV: Heterogeneous Capacitated Vehicles.*

Study	Product	Objectives	Model	Objective function components					Maxi distance criteria	Transport difficulty coefficient	HCV capacity constraint	Clustering based on		Clustering technique	Optimization approach
				FLC	FTC	VTC	OC	EC				Distance	Density		
Asgari et al. (2013)	Wheat	Single	LIP		✓	✓					✓				Lingo and GA
Khamjan et al. (2013a)	Sugar cane	Single	MIP	✓		✓					✓				Heuristic
Maiyar et al. (2015)	Grain	Single	MINLP			✓									SLPSO and PSOCP
Nourbakhsh et al. (2016)	Grain	Single	MIP	✓		✓	✓								Case study
Khamjan et al. (2013b)	Pig	Single	MIP			✓	✓				✓				Heuristic
Pathumnakul et al. (2012)	Sugar cane	Single	MIP	✓		✓						✓		MFCM and COG	Heuristic
Bosona and Gebresenbet (2011)	Meat	Single	LP			✓						✓		GIS software	Route LogiX software
Mohammadkhanloo and Bashiri (2013)	General	Single	MILP	✓		✓						✓		K-means with SA	GA
Zamar et al. (2017)	Bale	Single	MINLP			✓					✓	✓		K-means	Heuristic
Saranwong and Likasiri (2017)	Sugar cane	Single	MIP	✓		✓									Cplex and Heuristic
Sutanto et al. (2018)	General	Single	MIP			✓						✓		K-means	
Govindan et al. (2014)	Food	Multiple	MIP	✓	✓	✓	✓				✓				AMOVNS, NSGA-II and NRGA
Mohammed and Wang (2017)	Meat	Multiple	MILP			✓	✓								LP metrics and Epsilon constraint

Soysal et al. (2014)	Beef	Multiple	MIP		✓	✓					✓				Epsilon constraint
Validi et al. (2014)	Dairy	Multiple	MIP	✓		✓									NSGA-II and MOGA-II
Allaoui et al. (2018)	General	Multiple	MILP	✓		✓					✓				MCDM + Cplex
Current study	**Grain**	**Single**	**MILP**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**NKHGA**	**CPLEX**

Furthermore, few scholars have performed clustering based on distance using modified fuzzy c means, centre of gravity and K-means algorithms (e.g. Pathumnakul et al. 2012; Bosona and Gebresenbet 2011; Zamar et al. 2017; Sutanto et al. 2018). The density-based approach for clustering is overlooked in the studies mentioned above. Allaoui et al. (2018), Govindan et al. (2014) and Saranwong and Likasiri (2017) evaluated the location and transportation decisions. However, the capacity of optimal facilities constructed, and heterogeneous capacitated vehicles utilised are neglected in these studies. The integration of clustering algorithms to build a data-driven model that ensures the optimality in terms of the total cost for procurement of food grains is evident research gap, unexplored in the past literature. The study discussed in this paper presents an integrated mathematical model capturing the fixed cost of facility establishment, fixed and variable costs of transportation, operational and emissions costs. Critical influential parameters such as continuous capacity level, heterogeneous capacitated vehicle availability and transportation difficulty are incorporated in the proposed model.

3. Problem description

The policymakers in India have committed to ensuring a reasonable remunerative price called the minimum support price (MSP) to the farmers while procuring the food grain from them. By and large, all the procurement operations are confined to the regional level (district level). There are two major harvesting seasons, namely, '*Kharif*' and '*Rabi*' for food grains in India (Mahapatra and Mahanty 2018). Wheat is procured during *Rabi* (April to June) and rice in *Kharif* (October to February) harvesting seasons (Mogale et al. 2017b). Thus, two marketing seasons interweave with harvesting seasons. By considering various factors that affect the price of food grains, the government decides and fixes the MSP for a particular season. The government also declares several guidelines regarding quality of food grain that farmers have to ensure before they deliver them to the procurement centres. Based on the estimated procurement of every village, the FCI has to establish an adequate number of procurement centres with essential operations equipment like weighing machines, gunny bags, and cover plinths. Once the food grain is procured from farmers, it is stored at procurement centres and later shifted to central warehouses. Once food grains reach central warehouses, succeeding operations like distribution of food grains among regional warehouses and making accessible to the public fall out of the ambit of procurement stage.

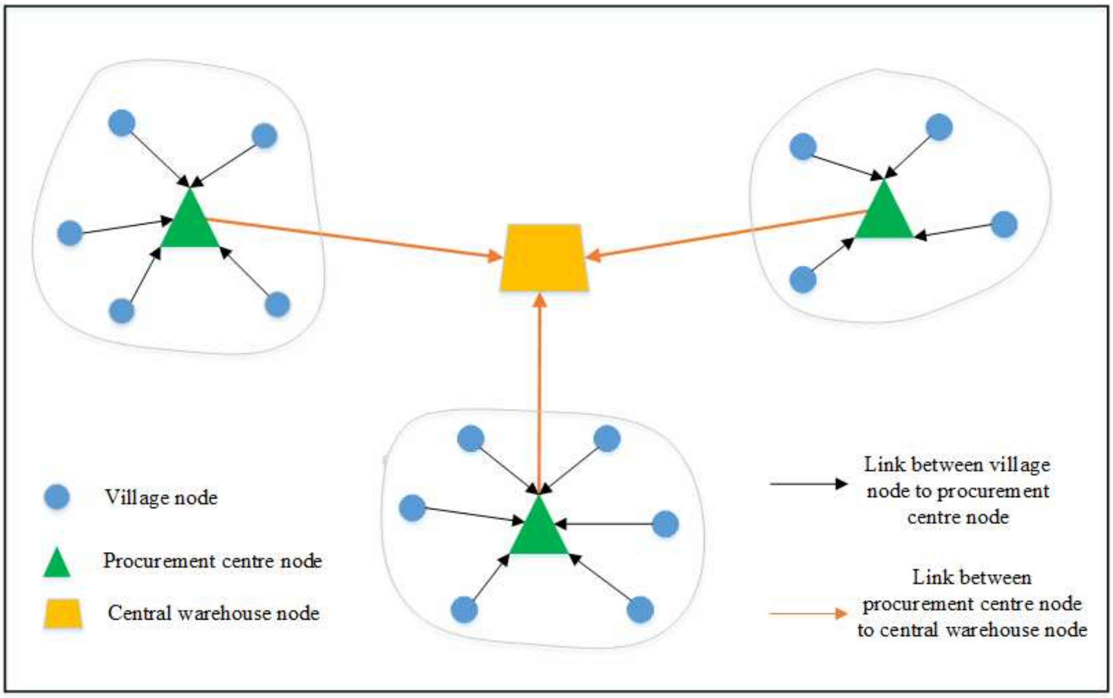

Figure 2 Pictorial representation of operations carried out in surplus states

There is an apparent scarcity of an appropriate number of procurement centres in India, especially in some of the surplus states (Pandey 2019). Figure 2 represents an overall view of operations carried out in surplus states in India. Currently, no scientific technique is being involved in the process of establishing a reasonable number of procurement centres and their respective economic geo-locations (Reddy et al. 2017). The lack of using reliable analytical models in the decision-making process is leading to frequent disruptions, resulting in the wastage of resources and increased inventory costs (Maiyar et al. 2015). Unscientific decisions made by policymakers are making these operations fragile (Mahapatra and Mahanty 2018). Multiple crucial parameters such as the convenience of farmers, distance from nearby villages to the procurement centres and central warehouses, availability of storage and transportation infrastructure, heterogeneous capacitated vehicle availability and capacity of central warehouses are not fully integrated while locating procurement centres (Reddy et al. 2017). Moreover, various other costs such as fixed cost of heterogeneous capacitated vehicles, operational cost and carbon emission cost need to be considered along with the variable transportation cost and infrastructure cost (Mogale et al. 2017b). The determination of an optimal number of procurement centres and their locations considering the parameters mentioned above are critical for increasing food grain procurement in India.

4. Mathematical formulation

The integrated model discussed in the paper is developed with the help of single objective formulation, which aims to minimize total supply chain network costs. This comprises of fixed costs of procurement centre establishment, fixed and variable transportation costs from villages to procurement centre and from procurement centres to central warehouses, operational costs and cost of transportation carbon emissions. The main objective of the model is to determine the optimal number and location of procurement centres within a select region. However, the model also provides optimal allocation, shipment quantity and heterogeneous capacitated vehicles used between villages to purchase centres and central warehouses. The formulation is static and avoids dynamicity of time window operations; because the dynamicity factor has hardly any impact in practice (Maiyar et al. 2015). Procurement centres are established for a three-month period during each harvesting season. The status of each procurement centre established is updated every week and food grains collected are trans-shipped to central warehouses/millers accordingly. Similarly, there are no time window stipulations in transporting the procurement from the procurement centre to central warehouses/millers. So, it is reasonable to avoid considering the dynamicity of time windows into the formulated model.

Assumptions:

1. The finite number of three types of heterogeneous capacitated vehicles (trucks) are considered at each echelon for grain movement. Entities involved in the food grain supply follow this approach.
2. The availability of grain and central warehouse capacities are known and deterministic.
3. Each vehicle carries Full Truck Load (FTL) transport.
4. Three types of difficulties, including low, medium and high, are considered while calculating the transportation costs. In India, the transportation infrastructure is poor. Hence, we have considered this assumption and integrated into the model. The description and mathematical equations of these three difficulties are depicted below.

   Low difficulty means the road that connects the particular village to the nearest procurement centre is in good condition. Therefore, farmers can take this route to reach to the procurement centre, and standard transportation costs are incurred for this movement. Similarly, this condition is applicable while transferring the food grain from procurement centres to central warehouses.

   For low difficulty coefficient: Transportation cost = 1 × transportation cost.

Medium difficulty means the road that connects the particular village to the nearest procurement centre is not in good condition. Therefore, farmers have to take another (longer) route to reach to the procurement centre, and they have to pay additional costs for this route compared to the standard (shorter) route. In this case, we have assumed that farmers have to pay the 25% additional cost for the medium difficulty level.

For medium difficulty coefficient: Transportation cost = 1.25 × transportation cost.

Similarly, for high difficulty, we have assumed that farmers pay 50% additional costs.

For high difficulty coefficient: Transportation cost = 1.50 × transportation cost.

Notations

Set	Index	Definition
V	v	Village
P	p	Candidate sites for procurement centre
R	r	Central warehouses or temporary storage points
L	l	Available vehicle types at village level
K	k	Available vehicle types at procurement centre
D	d	Difficulty coefficient

Parameters	Description
fc_p	Fixed cost of establishing a procurement centre at candidate location *p* (USD)
uc_l	Fixed cost of transportation for vehicle of type *l* (USD /vehicle)
uc_k	Fixed cost of transportation for vehicle of type *k (*USD /vehicle)
c_{vp}^d	Variable cost of transportation per unit weight (Metric ton) per unit distance with difficulty coefficient *d* from village *v* to procurement centre *p* (USD /MT/km)
c_{pr}^d	Variable cost of transportation per unit weight (Metric ton) per unit distance with difficulty coefficient *d* from procurement centre *p* to central warehouse *r* (USD /MT/km)
π	Operational cost per unit weight (Metric ton) at procurement centre (USD/MT)
λ	Cost of per unit carbon dioxide emission (USD /kg)
e_{vp}^d	Distance with difficulty coefficient *d* from village *v* to procurement centre *p* (Km)

e_{pr}^{d}	Distance with difficulty coefficient d from procurement centre p to central warehouse r (Km)
Q	Maximum acceptable service or coverage distance from village v to procurement centre p (Km)
I_v	The set of procurement sites p within an acceptable distance of village v
a_v	Amount of food grain quantity available at village v for procurement (MT)
h_r	Storage capacity of central warehouse r (MT)
ω_l	Capacity of vehicle type l (MT)
Ω_k	Capacity of vehicle type k (MT)
η_{lv}	Total number of l type of vehicles available at village v (Number)
ρ_{kp}	Total number of k type of vehicles available at procurement centre p (Number)
s_{vp}^{dl}	Amount of CO_2 released per unit distance with difficulty coefficient d for each l type of vehicle travelling from village v to procurement centre p *(Kg/km)*
s_{pr}^{dk}	Amount of CO_2 released per unit distance with difficulty coefficient d for each k type of vehicle travelling from procurement centre p to central warehouse r *(Kg/km)*
M	A sufficiently large number

Decision variables	
X_p	Equal to 1 if the procurement centre is established at potential site p and equal to 0 otherwise
Y_{vp}	Equal to 1 if the village v is assigned to procurement centre established at potential site p and equal to 0 otherwise
Y_{pr}	Equal to 1 if the procurement centre established at possible site p is assigned to central warehouse r and equal to 0 otherwise
J_p	Capacity of the procurement centre that is established at potential site p

W_{vp} Amount of food grain quantity transported from village v to procurement centre at location p

G_{pr} Amount of food grain quantity transported from procurement centre at location p to central warehouse r

B_{vp}^{l} Number of vehicles of type l used to transport the food grain from village v to procurement centre p

N_{pr}^{k} Number of vehicles of type k used to transport the food grain from procurement centre p to central warehouse r

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Objective function

Min total supply network cost = Procurement centre establishment cost + Fixed and variable transportation cost from villages to PPC + Fixed and variable transportation cost from PPC to central warehouse + Operational cost + Cost of carbon dioxide emission generated due to transportation.

$$\begin{aligned}&\sum_{p\in P} fc_p X_p + \sum_{v\in V}\sum_{p\in P}\sum_{l\in L}\sum_{d\in D}\left(uc_l B_{vp}^{l} + c_{vp}^{d} e_{vp}^{d} W_{vp}\right) + \sum_{p\in P}\sum_{r\in R}\sum_{k\in K}\sum_{d\in D}\left(uc_k N_{pr}^{k} + c_{pr}^{d} e_{pr}^{d} G_{pr}\right)\\ &+\left[\sum_{v\in V}\sum_{p\in P} W_{vp} + \sum_{p\in P}\sum_{r\in R} G_{pr}\right]\pi + \left[\sum_{v\in V}\sum_{p\in P}\sum_{l\in L}\sum_{d\in D} s_{vp}^{dl} e_{vp}^{d} B_{vp}^{l} + \sum_{p\in P}\sum_{r\in R}\sum_{k\in K}\sum_{d\in D} s_{pr}^{dk} e_{pr}^{d} N_{pr}^{k}\right]\lambda\end{aligned} \quad (1)$$

The objective function (1) is the minimization of the total supply chain network cost. This cost includes (a) establishment cost of procurement centre, (b) fixed and variable transportation cost from village to procurement centre, (c) fixed and variable transportation cost from procurement centre to central warehouse, (d) operational cost at procurement centre and (e) cost of carbon dioxide emission generated due to transportation activities.

Subject to constraints

$$W_{vp} \le a_v \qquad \forall v, \forall p \qquad (2)$$

Constraint (2) does not allow the transport of the food grain from village v to a particular procurement centre more than its availability at village v.

$$W_{vp} \le MY_{vp} \qquad \forall v, \forall p \qquad (3)$$

Constraint (3) is a big M constraint and it indicates that food grain is transferred on only assigned nodes.

$$Y_{vp} \le X_p \qquad \forall v, \forall p \qquad (4)$$

Village v is assigned only to the established procurement centre at potential site p and this is shown by Constraint (4)

$$\sum_{p \in P} Y_{vp} = 1 \qquad \forall v \qquad (5)$$

Each village can transfer food grains to only one procurement centre, and Constraint (5) is used to depict this condition.

$$G_{pr} \le J_p \qquad \forall p, \forall r \qquad (6)$$

$$G_{pr} \le \sum_{v \in V} W_{vp} \qquad \forall p, \forall r \qquad (7)$$

Food grain quantity transferred from each procurement centre to a specific central warehouse should be less than or equal to the storage capacity of procurement centres. This is illustrated by Constraint (6). Further, the capacity of the procurement centre is equal to the sum of the procurement of villages assigned to that procurement centre. Hence, it can also be written like Constraint (7).

$$G_{pr} \le MY_{pr} \qquad \forall p, \forall r \qquad (8)$$

Constraint (8) is a big *M* constraint and is used for describing the relationship between the two decision variables (G_{pr} and Y_{pr}).

$$Y_{pr} \le X_p \qquad \forall p, \forall r \qquad (9)$$

Constraint (9) indicates that only established procurement centres can be assigned to the central warehouses.

$$\sum_{p \in P} G_{pr} \le h_r \qquad \forall r \qquad (10)$$

The amount of food grain transferred from all procurement centres to the central warehouse should be less than or equal to the storage capacity of the central warehouse. This is delineated by Constraint (10)

$$\sum_{r \in R} Y_{pr} = 1 \qquad \forall p \qquad (11)$$

Constraint (11) shows that each procurement centre can transfer the food grain to only one central warehouse.

$$\sum_{p \in I_v} X_p \geq 1 \qquad \forall v \qquad (12)$$

Constraint (12) enforces that for each village *v,* at least one procurement centre must be established within set I_v of potential procurement centres.

$$W_{vp} \leq \sum_{l \in L} \omega_l B_{vp}^l \qquad \forall v, \forall p \qquad (13)$$

$$B_{vp}^l \leq \eta_{lv} \qquad \forall v, \forall p, \forall l \qquad (14)$$

The vehicle capacity constraint between village *v* and procurement centre *p* is depicted by Constraint (13). Furthermore, number of vehicles used should be less than or equal to their availability (Constraint 14).

$$G_{pr} \leq \sum_{k \in K} \Omega_k N_{pr}^k \qquad \forall p, \forall r \qquad (15)$$

$$N_{pr}^k \leq \rho_{kp} \qquad \forall p, \forall r, \forall k \qquad (16)$$

Constraint (15) makes sure that the quantity transferred from the procurement centre to the central warehouse is within vehicle capacity restrictions. Constraint (16) ensures that the number of vehicles used from the procurement centre to central warehouse must lie within its maximum availability.

$$X_p \in \{0,1\} \qquad \forall p \qquad (17)$$

$$Y_{vp} \in \{0,1\} \qquad \forall v, \forall p \qquad (18)$$

$$Y_{pr} \in \{0,1\} \qquad \forall p, \forall r \qquad (19)$$

Constraint sets (17) to (19) represent the binary variables.

$W_{vp} \geq 0 \qquad \forall v, \forall p \qquad (20)$

$G_{pr} \geq 0 \qquad \forall p, \forall r \qquad (21)$

The non-negativity constraints are denoted by Constraints (20) and (21).

$B_{vp}^{l} \in \mathbf{Z^{+}} \qquad \forall v, \forall p, \forall l \qquad (22)$

$N_{pr}^{k} \in \mathbf{Z^{+}} \qquad \forall p, \forall r, \forall k \qquad (23)$

The integer constraints are denoted by Constraint (22) and (23).

5. Solution approach

5.1 Existing approaches

Multiple clustering techniques including hierarchical, density-based, partitioning and grid-based clustering can be employed to examine the present model. However, several drawbacks of these techniques are discussed in the previous studies. Sensitivity to noise and outliers and computational complexity are two major drawbacks of hierarchical clustering algorithms (Saraswathi and Sheela 2014). Density-based clustering techniques are highly sensitive to the set of input parameters, and they cannot handle the clusters of different size (Han et al. 2011). The K-means clustering algorithm requires a number of clusters as an input and the algorithm does not converge to a global optimum. Furthermore, the algorithm is sensitive to noise and outliers, which may lead to objects being assigned to the wrong clusters. Furthermore, most partition-based algorithms usually find spherical shaped clusters; hence, they are not efficient while working with clusters of arbitrary shape (Xu and Wunsch 2005; He and Tan 2012).

The complexity of models increases with food product characteristics and advanced algorithms are needed to solve them (Esteso et al. 2018, Golini et al. 2017; Yakovleva et al. 2012). A comprehensive review of nature-inspired metaheuristic algorithms employed for partition clustering and automatic clustering is presented by Nanda and Panda (2014) and José-García and Gómez-Flores (2016). Recently, Tinós et al. (2018) propose an NK Hybrid Genetic Algorithm for clustering which is based on near neighbour influence; hence it does not require several clusters as input and thereby serves both purposes efficiently. Another significant advantage of using the NK Hybrid algorithm is that it works efficiently in datasets with noise. The algorithm also allows detection of arbitrary shapes and automatically determines the number of clusters. This algorithm generated superior results compared with other GA approaches and state-of-the-art clustering algorithms (Tinós et al. 2018). Therefore, this paper adapted NKHGA to cluster several villages based on distance and density of villages.

5.2 NK hybrid genetic algorithm

The solution consists of a bi-level approach for solving the formulated problem. Initially, the villages are grouped into clusters based on a distance-density metric, and each of this cluster is allocated to a respective candidate location of procurement centres. In the second level, a group of procurement centres are assigned to the individual central warehouses. The clustering of villages is done using NK Hybrid Genetic Algorithm (NKHGA), which is based on near neighbour influence. After grouping of villages into respective clusters, all feasible tentative procurement centre sites are selected based on a Gaussian density approach, and the complete model is solved using python.

NKHGA is a clustering algorithm, based on NK clustering validation criterion 2 (NKCV2) which is a new version of NK clustering validation (NKCV) criterion proposed by Tinós et al. (2016). The NKCV function is broken into N (total number of objects) sub-functions each of which depends on a local group of K+1 objects of the dataset where K << N. The major modification in NKCV2 criterion is that it uses the density of objects along with the distance between objects. Thus, providing robust results in datasets with noise. To find these K+1 objects which affect a particular sub-function, an interaction graph is prepared based on distance and density of objects. Distance is measured using general Euclidean distance, whereas, a Gaussian kernel function is used for calculating local density. With respect to the algorithm, each village v_i is associated with a local density (ρ_i). The density of the village is captured by equation (24). Observe that a pairwise computation of the contribution to the density occurs for each village i. This is because the distance of v_i with all the other villages is compared for their contribution to the final density. In an interaction graph, each solution vector is represented by a vertex, and each edge indicates a particular element influencing certain sub-functions.

$$\rho_i = \sum_{j=1}^{N} K\left(y_i - y_j\right) \tag{24}$$

$$K\left(y_i - y_j\right) = e^{\frac{-\|y_i - y_j\|^2}{2\epsilon^2}} \tag{25}$$

Equation (25) is the kernel of the density function. Such a kernel function allows for more precise value of the density function because it takes real values in the range of 0 and 1 in contrasts to only integer values. In the denominator, ϵ is the cut-off distance and is a parameter of our choice. The higher the value of ϵ, the curve is more widely spread, and a lower value corresponds to the kernel function being spread more sharply near zero. Therefore, based on the order of value of norm$\| y_i - y_j \|$, ϵ is to be chosen such that the kernel function is able to rightly discriminate between the value to be assigned to the kernel and, therefore, its contribution to the density.

In this paper, a density-based methodology is adopted for selecting candidate locations for the establishment of procurement centres. The proposed method selects the required number of candidate locations from the given set of villages based on the Gaussian density of the villages and a minimum cut-off distance. The villages are first sorted in descending order based on their Gaussian density.

The population consists of a fixed number of individuals, which is optimized using local search. The local search uses an interaction graph and delta evaluation to speed up the computations. Finally, the object is assigned to the cluster for which the value of delta is most negative. The object to be reallocated is randomly selected. This process is repeated for a fixed number of iterations.

Once the population is initialized, the best individual is selected from the population using elitism and tournament selection. Partition crossover is applied at a fixed rate. A deterministic recombination operator called PX, proposed by Whitley et al. (2009) for the travelling salesman problem and this PX operator, is used as a crossover in this paper. In this method, a weighted graph is prepared from the union of the two-parent solution. The evaluation function is decomposed by finding connected components in the weighted graph. Hence, the evaluation function of the offspring can be decomposed into two functions, each of which is a partial evaluation of only one parent solution. Before applying crossover, mapping of labels of one parent solution to the other parent is done using a renumbering process. Once the crossover is completed, clusters with the same label are relabelled. The flowchart of the proposed NK hybrid genetic algorithm is given in Figure 3.

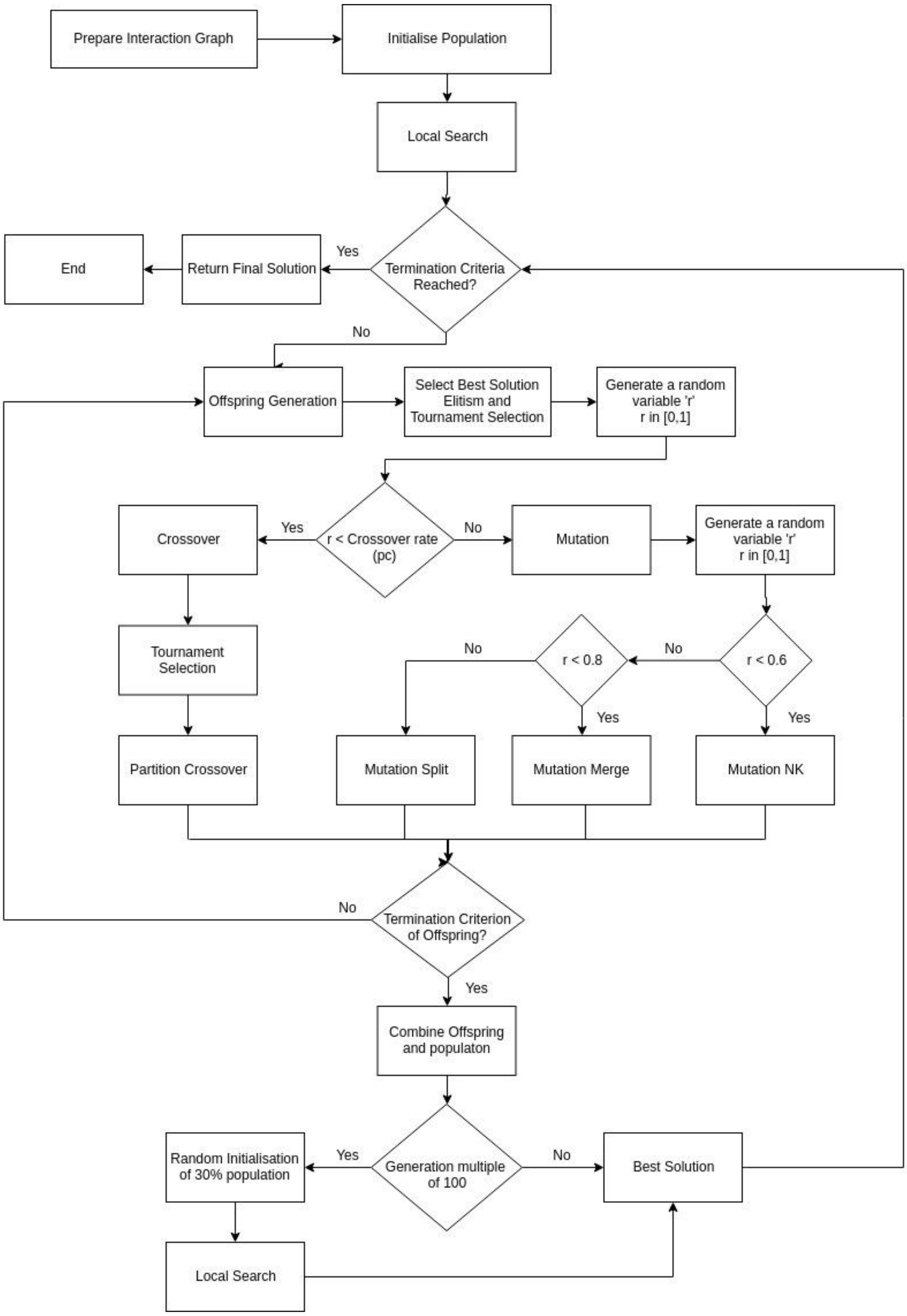


Figure 3 Flow diagram for NKHGA implementation

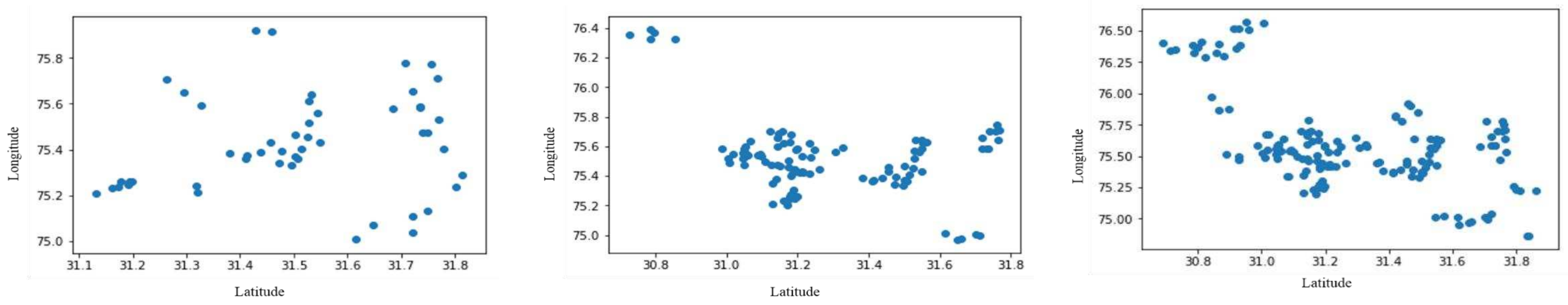
The proposed NKHGA was implemented in Python 3.6 and executed on an Intel Core i5 2.90 GHz processor with 8 GB RAM under a Windows 8 environment. Several preliminary computational experiments were conducted for setting of the algorithmic parameters of NKHGA. The tuned algorithm parameters considered are as follows: (1) population size = 100,

(2) epsilon = 2, (3) K = 3, (4) crossover probability = 0.6, (5) number of iterations of main algorithm = 300 and (6) number of iterations of local search = 20.

6. Context of the study

The proposed mathematical model is implemented on three real-life cases including small, medium and large datasets from the northern part of India. Major states in North India are the producer of wheat; hence, these cases belong to the wheat-food grain supply chain network. The data of the financial year 2015-16 related to Kapurthala, Moga, and Amritsar districts of Punjab is collected for small, medium and large cases respectively. The geographical location of different villages and tentative locations of procurement centres in the form of their latitude and longitude is extracted from Google Maps. The Kapurthala district comprises of 50 villages that participated in the procurement operations in 2016 *Rabi* harvesting season as shown in Figure 4(a) with their latitude and longitude. This district contains a pool of eight central warehouses. Similarly, 100 villages from Moga and 150 villages from Amritsar districts sold their produce to state agencies in 2016 during *Rabi* harvesting season. Figures. 4(b) and (c) depict the geographical locations of villages from Moga and Amritsar districts respectively.

Moga and Amritsar districts consist of 20 and 30 central warehouses, respectively. Most of the data were collected through field visits to different FCI offices, several reports including the Comptroller and Auditor General of India (CAG) report 2013, high-level committee report 2015 and online portals such as the FCI portal (http://fci.gov.in) and PDS Portal of India (http://pdsportal.nic.in/main.aspx). It was challenging to obtain real-time data associated with few parameters; in such cases, appropriate assumptions or ranges were considered. These data include estimated procurement of village-wise data, fixed cost and vehicle resource availability. The average handling capacity of purchase centres is determined from the total procurement of district. Table 2 presents the values of model parameters.



(a) (b) (c)

Figure 4: Geographical location of villages of (a) Kapurthala district, (b) Moga district and (c) Amritsar district

Table 2 Model parameters and associated values

Parameters	Range of values	Parameters	Range of values
fc_p	USD 28880-57760	a_v	50-200 MT
uc_l	USD 7.22-14.44	h_r	25000-100000 MT
uc_k	USD 21.66-28.88	I_v	1-3
c_{vp}^d	USD 0.29	ω_l	5-10 MT
c_{pr}^d	USD 0.29	Ω_k	15-20 MT
π	USD 2.89	η_{lv}	5-40
λ	USD 5.78	ρ_{kp}	20-80
e_{vp}^d	3-15 km	s_{vp}^{dl}	0.01-0.02
e_{pr}^d	15-40 km	s_{pr}^{dk}	0.03-0.04
Q	15 km	M	1000000000

7. Results and Discussion

Initially, the small size case comprising of 50 villages, 20 potential procurement centre locations ande 8 central warehouses was solved. NKHGA grouped 50 villages into 12 clusters, which are depicted in Figure 5 with different colours and markers. Different arbitrary shape of clusters formed confirm the capability of the proposed algorithm (Figure 5). Further, Table 3 shows the indices of these villages that are pooled into different clusters in the region. The proposed algorithm took 436 seconds (computational time) to solve the small size problem. The clusters were optimally assigned to the various procurement centres so that farmers can sell their food grains to the assigned government purchase centre. This optimal tagging of clusters to procurement centres is illustrated in Figure 6.

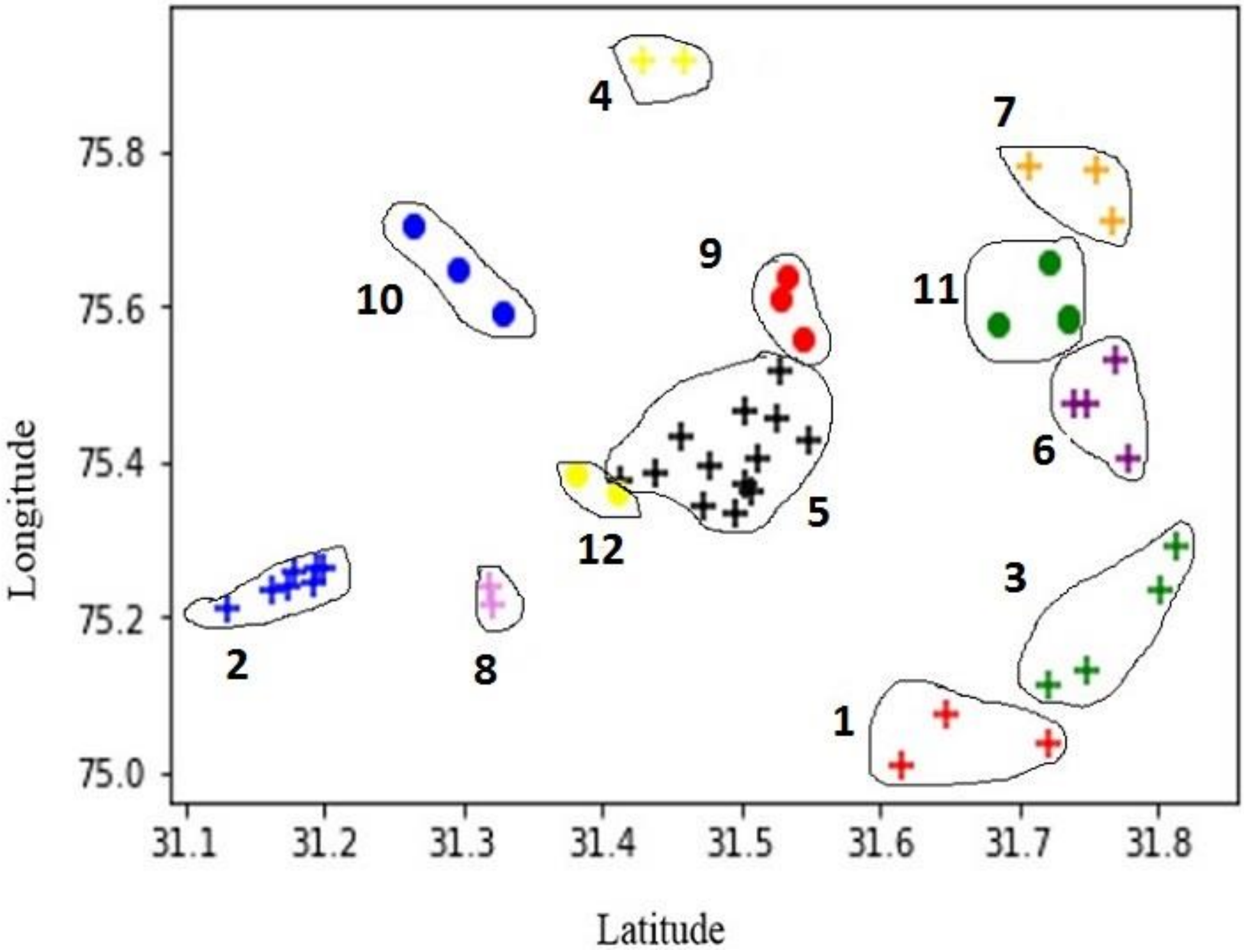


Figure 5 Clustered villages of Kapurthala district

Table 3 Optimal clusters of villages obtained

Cluster Index	Set of Villages in the Cluster	Cluster Index	Set of Villages in the Cluster
1	{1, 29, 30}	7	{8, 27, 35}
2	{2, 14, 34, 37, 41, 45, 49}	8	{10, 33}
3	{3, 9, 21, 42}	9	{11, 20, 46}
4	{4, 26}	10	{12, 17, 32}
5	{5, 6, 15, 19, 24, 31, 36, 38, 39, 40, 43, 44, 48}	11	{13, 22, 23, 47}
6	{7, 16, 18, 50}	12	{25, 28}

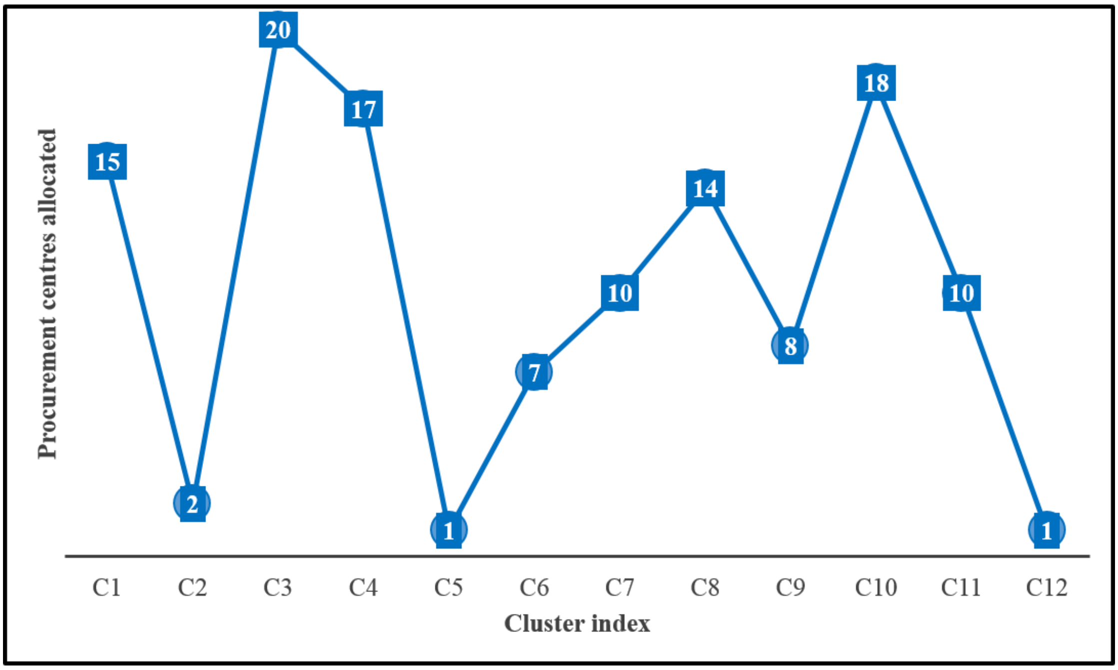


Figure 6 Optimal tagging of clusters to procurement centres

Similarly, the optimum quantity transferred from the procurement centre to central warehouses is determined and reported in Table 4. The 1 and 0 depict the assignment and no assignment between the procurement centre and central warehouses, respectively. In case of allocation, the shipment quantity is indicated in the bracket. The capacity of the procurement centre to be established is calculated by adding quantity purchased from villages assigned to that procurement centre. Figure 7 shows the capacity of the different established procurement centres.

Table 4 Tagging of procurement centre to central warehouse and shipment quantity

Procurement Centre	CW1	CW2	CW3	CW4	CW5	CW6	CW7	CW8
1	0	0	0	0	0	0	0	1(1872)
2	0	0	0	0	0	0	0	1(928)
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	1(580)	0	0	0
8	0	0	1(247)	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	1(879)	0	0	0
11	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	1(171)
15	1(557)	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0
17	0	0	1(256)	0	0	0	0	0
18	0	1(380)	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	1(527)	0

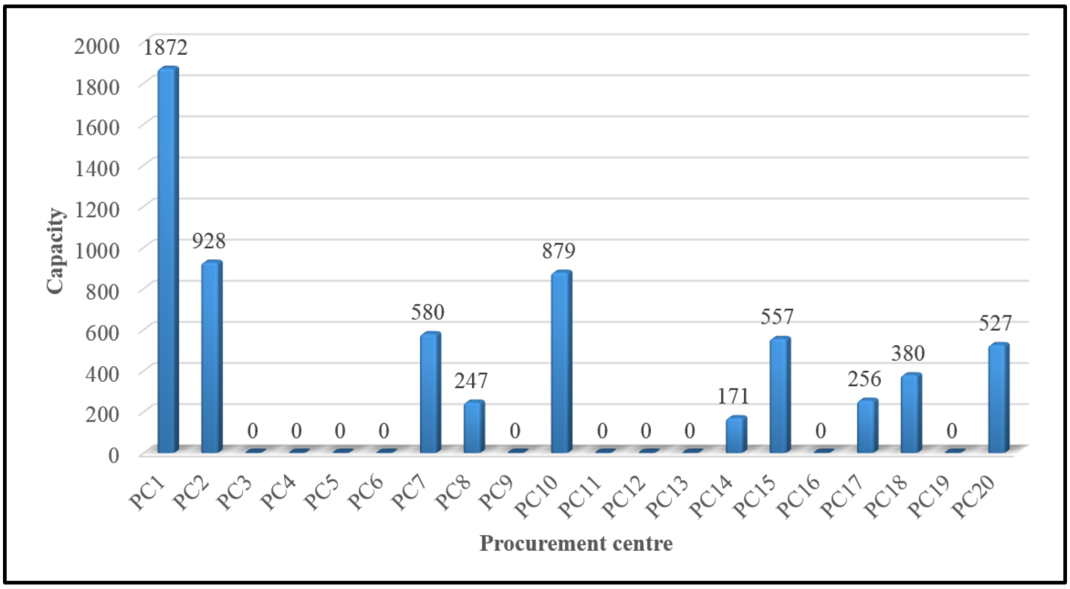


Figure 7 Capacity of procurement centres established

The proposed approach has been verified and validated with medium (Moga district) and large (Amritsar district) size datasets. Due to the rise in the number of villages, potential procurement centre locations, centre warehouses, number of decision variables and constraints have drastically increased (Table 5). The summary of results for all three case types, along with computational time, the number of clusters produced, and procurement centres established, is provided in Table 5. The clusters produced for medium and large data sets are not illustrated in any figure due to the brevity of different colours and markers. It can be seen from Table 5 that the number of clusters produced, and procurement centres established increased for case 2 compared with case 1. Similar changes in the number of clusters produced and procurement centres established with different numerical values are perceived for case 3. In the present situation, the economic and welfare growth rate of farmers is low, and most of the farmers are not receiving MSP for their produce due to unavailability of government procurement centres in their nearby area. However, now farmers can sell their produce to these newly established procurement centres within fifteen km radius of any village and get the benefits of the MSP. Due to the establishment of these purchase centres, farmers travel fewer distances to reach the nearest procurement centres for selling their produce, leading to less transportation cost, travel time and carbon emission. Further, the post-harvest losses due to open storage of food grain stock get reduced through the construction of purchase centres. The quality of the food grain is also kept intact through the secure storing of food grain stock in procurement centres.

Table 5 Summary of overall results for all three cases (All costs in USD)

	Case 1 (Kapurthala District)	**Case 2 (Moga District)**	**Case 3 (Amritsar District)**
Establishment cost	412391.79	587591.97	1000353.06
Transportation cost	75607.02	160765.54	247282.91
Operational cost	36949.07	71408.69	106243.74
Environmental cost	42721.75	266747.20	628691.37
Total cost	568818.78	1093990.40	1998817.59
NKHGA time (s)	436.115	1114.17	4490.91
Clusters produced	12	17	26
Procurement centres established	10	14	23
Number of variables	5840	24080	54120
Number of constraints	15908	65100	146250

To obtain further insights, a sensitivity analysis was conducted on two key important model parameters, namely the number of villages and maximum distance between villages and nearest procurement centre. Also, we have evaluated the effect of algorithmic parameter K, which influences each object in the dataset. All these experiments were performed on the small size case study.

Effect of variation in number of villages

The number of villages participating in the procurement process is important for efficient food supply chain network. Thus, it is essential to explore the impact of change in the number of villages. We have varied the number of villages from -40% to +40% of its current values and its effect on the objective function is depicted in Figure 8. Similarly, the repercussion on optimal cluster generated (C) and procurement centres established (P) is displayed in the same figure. It is observed that increasing the number of villages resulted in forming more clusters and establishing more procurement centres to cover the additional villages and associated food grain quantity in the designed network. Due to the establishment of more procurement centres, establishment costs increase, which forms a significant portion of the total cost. Transportation, operational and environmental costs are also enhanced with increase in the number of villages. The different acronyms used in Figure 8 are described as follows: *Esta cost: Establishment cost, Opr cost: Operational cost, Tras cost: Transportation cost, Env cost: Environmental cost and Tot cost: Total cost.*

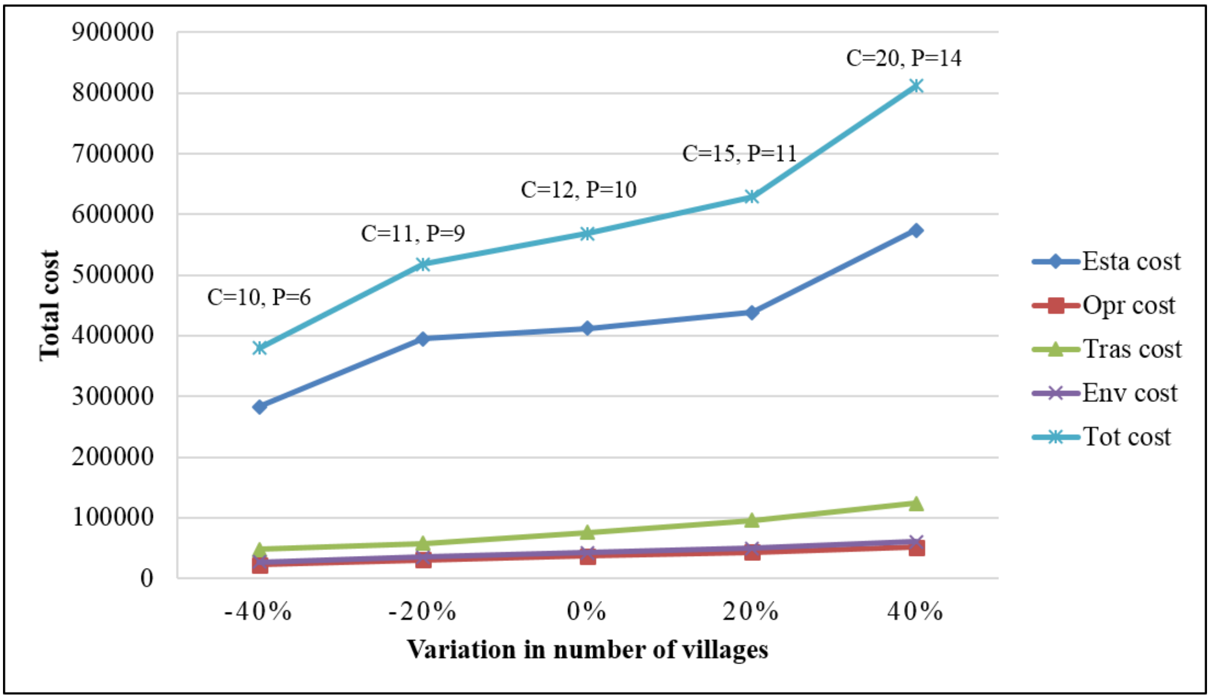


Figure 8 Effect of variation in number of villages on objective function and its components

Effect of distance between the village and nearest procurement centre

As mentioned earlier, at least one procurement centre should be available within a given radius from any villages, so that farmers can effectively sell their produce to government agencies and take the benefits of the MSP. Hence, we analysed this distance parameter to capture the impact on total cost and cluster formations. Figure 9 illustrates changes in total cost and its components over a range of maximum distance parameter. The number of clusters formed and procurement centres established are augmented after the reduction of maximum distance (Figure 9). According to this figure, a decrease in the value of maximum distance increases fixed establishment cost, which also escalates the total cost by 9%. However, the operational cost remains unchanged. Farmers have to travel less distance to reach the nearest procurement centre in case of decreased maximum distance; thus, transportation and environment costs also reduces. Overall, there is a negative relationship between the maximum distance and procurement centres established (fixed establishment cost). The increment in the maximum distance positively influences the total cost, including transportation and environmental cost.

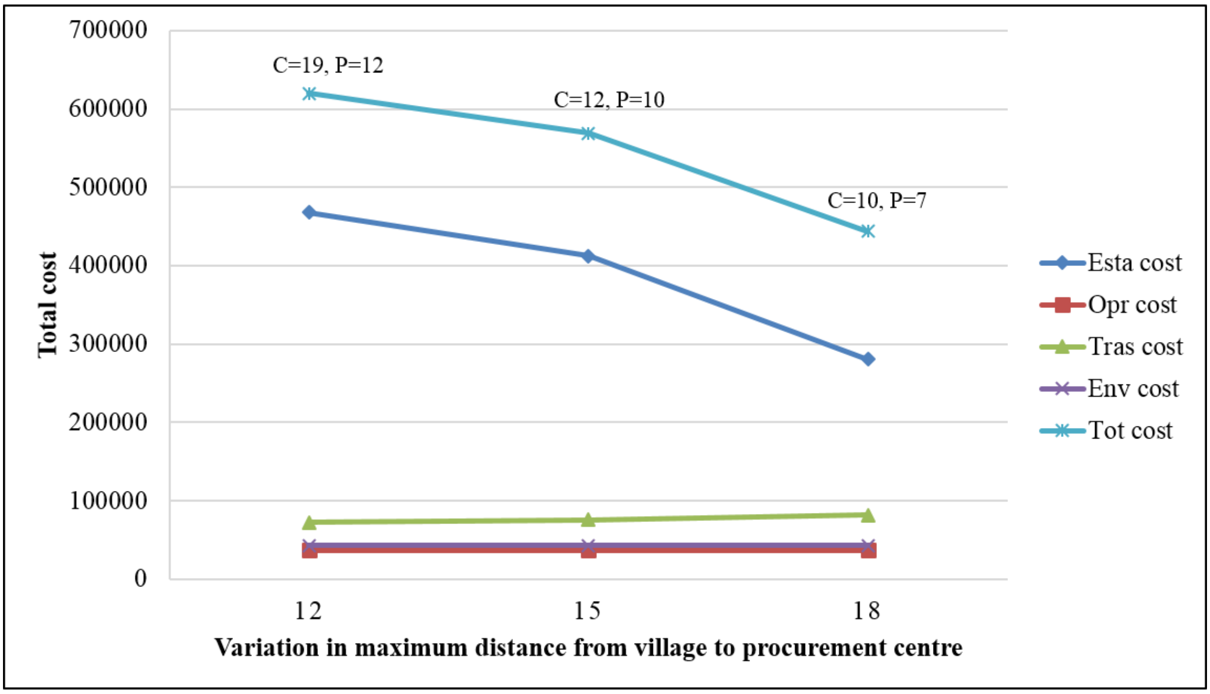


Figure 9 Effect of variation in the maximum distance from village (v) to procurement centre (p) on objective function and its components

Effect of variations in parameter (K)

In the NKHGA, *N* corresponds to the number of elements or objects in the dataset to be clustered and K is the parameter which influences each object in the dataset. The parameter K is used while calculating the density of the particular village (Eq. 24). In our case, each village is influenced by number of nearby villages (K). The effects of changing parameter K from 2 to 5 is represented in Figure 10. With a rise in value of parameter K, the establishment cost increases, which also increases the total cost. This means that a number of procurement centres established remain the same, but their locations are changed, leading to an increase in the total cost. The transportation and environmental cost reduced up to K=4 and increased from K=5. The operational cost remains unaffected to variation in parameter K.

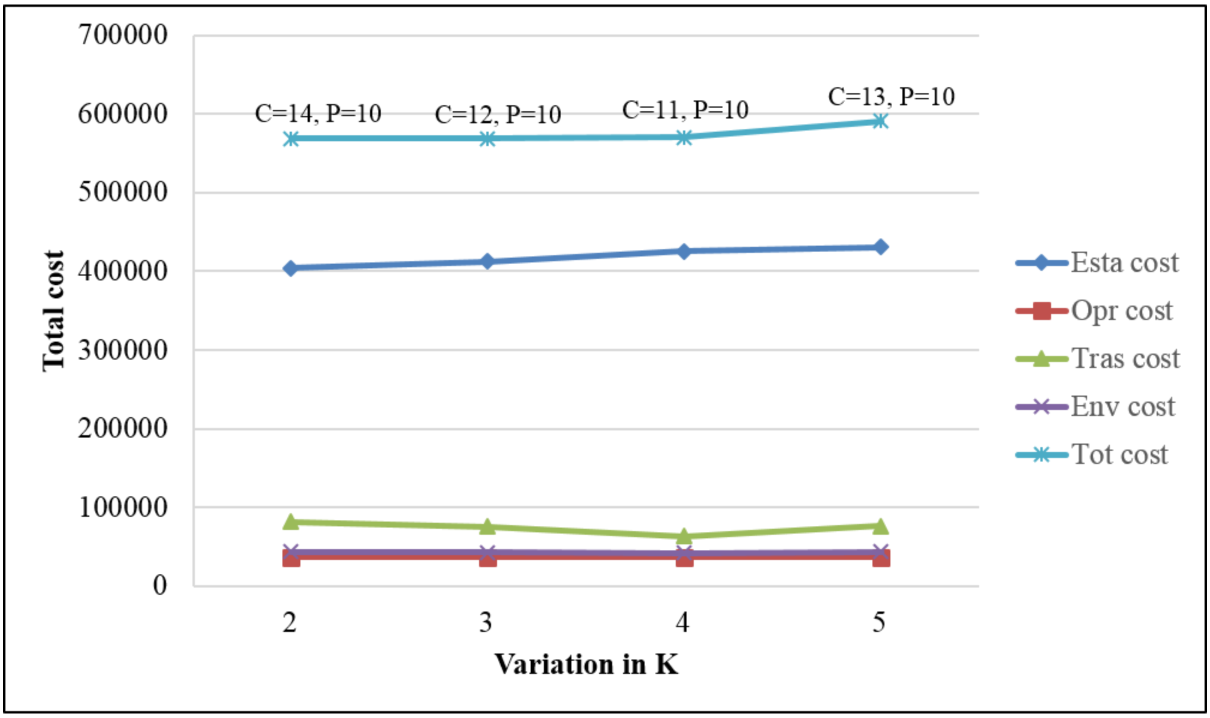


Figure 10 Effect of variation in parameter K on objective function and its components

8. Contribution and further research

The study aimed to develop an integrated analytical model to make informed decisions for the procurement of food grains. Following the development and assessment of a robust data-driven model, the paper provides scientific evidence for developing procurement policy for food grain supply chain network. The model considered economic and environmental dimensions of sustainability by including freight transportation and carbon emission costs. The study presented a practical method for the integration of machine learning tools like clustering algorithms with optimization to solve complex models. Small, medium and large size cases from Indian food grain supply chain network were utilised to test the proposed model. Sensitivity analysis results indicate that government and policymakers should focus on creating an adequate number of procurement centres in each surplus state, before the start of the marketing season. This will help farmers in gaining maximum benefit from the MSP decided by the government agencies.

Few managerial implications can be drawn from the study. The insights developed through the present study would be helpful to the management authorities for robust planning and coordination activities. For example, the FCI can group several villages into different clusters identified in the proposed algorithm. Since the establishment of procurement centres is the most significant element in the total cost, policymakers have to pay special attention to the determination of optimal locations. This study will be also beneficial to farmers in making the best out of MSP, by selling their produce to nearby procurement centre. This will lead to an improvement in their economic and welfare growth. This will further enhance farmer's interest in producing and selling food grains to nearby procurement centres, which is one of the main objective of FCI.

There are also few policy implications of the study. Farmers will travel fewer distances to reach the nearest procurement centres, which helps them to reduce transportation cost, time and emission. The availability of an adequate number of procurement centres in the surplus states boosts the procurement, which leads to escalating central food grain stock. One of the major focus of policymakers in India to feed the ever-growing population. The food loss due to open storage would significantly reduce after the establishment of sufficient procurement centres in several surplus states. The major issue of deterioration of food quality will also be resolved through the proposed policy implications. Farmers will be aware of the MSP and government's support for their produce. Additionally, the timely information about the MSP and adverse climatic conditions will be appropriately disseminated among the farmers due to the availability of procurement centres in the nearby areas. In addition to the above, the decisions made through the model also helps to enhance sustainability in the food grain supply chain network. The management authorities can add the rice miller as an additional echelon between the procurement centres and central warehouses to transform this model for rice supply chain problem.

The paper has few limitations, which paves the way to future research avenues. The model considered deterministic parameters and thus, stochastic procurement can be considered to capture uncertainties in future studies. Integration of the social dimension of sustainability lacked in the current model. Thus, the maximization of social benefits can be considered as a second objective in the revised model. The optimization of transit time to reduce post-harvest losses is another possible extension to this study. Nevertheless, the proposed work provides a strong foundation for modelling complex food supply chain models to capture real-time issues in developing countries, typically lacking infrastructure and processes.

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